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Partially Averaged Navier Stokes simulation of turbulent heat transfer from a square cylinder

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ABSTRACT

A variable resolution modeling approach, namely the Partially-Averaged Navier Stokes (PANS) approach, is used to study heat transfer in a separated turbulent flow field. The simulations are performed to assess the applicability and effectiveness of the PANS approach. Two types of grids are compared: a structured grid with full hexahedral elements with wall functions model (SM-WF) and an unstructured grid with hybrid tetrahedral-prismatic elements with wall resolve model (UM-WR). A heated square cylinder in cross air stream at $Re = 2.2 \times 10^4$ is considered and the simulations are performed using a finite volume based opensource software, OpenFOAM. It is observed that the PANS approach, with both the meshing strategies adopted, is able to predict the unsteady flow behavior around the cylinder and in the wake. But, only the wall resolve case reproduces the thermal and the Nusselt number behaviors around the cylinder as compared to experimental results. Further the wall resolve model is used to study the heat transfer phenomena at different faces of the cylinder over a complete vortex shedding cycle using the phase-averaged analysis of the shedding phenomenon. The turbulent heat fluxes are also studied to understand the effect of turbulence on convection.

1. Introduction

Forced convection from a bluff body situated in a cross flow is a major issue encountered in many practical situations, such as, cooling towers, heat exchangers, turbo-engines and electronic equipment cooling. Heat transfer in these cases is generally due to turbulence and predicting such kind of flows is difficult on account of various complex characteristics, such as, vortex shedding, separation, and interaction of separated shear layers, associated with it. Understanding the influence of these flow characteristics on heat transfer from a body is indispensable for efficient and economical construction of heat exchanging devices. In this context, the modeling technique, to be used, should be able to accurately capture all the aforementioned flow physics. Conventionally, industries have been using the Reynolds-Averaged Navier–Stokes (RANS) methodology, based on the statistical approach. This methodology fails to predict 3D fluctuating components of a complex flow field. On the other hand, Large Eddy Simulation (LES) can be an option but, it requires large computational resources and it is very sensitive to grid type used, thus making it difficult for the industries to use it. The aim of the present study is to use a variable resolution model and to show its applicability with any grid type using small computational effort, for problems concerning convective heat transfer from a bluff body in a cross-flow.

Many variable resolution modeling approaches have been proposed by researchers. Recently Girimaji and his associates [1,2] proposed Partially-Averaged Navier Stokes (PANS) approach, based on the RANS paradigm to partially resolve the large eddies and model the smaller eddies using two equation models. They showed that the PANS approach can commute from RANS approach to DNS depending on the filter width used. The filter width is given by two parameters, the ratio of unresolved-to-total kinetic energy (f_k) and the ratio of the unresolved-to-total dissipation (f_ε), and by defining these parameters a desired level of physical resolution can be achieved between RANS and DNS. Many researchers [3–6] have used the PANS approach, based on various RANS models, to predict various flow fields with desired variable resolution and showed the applicability of PANS approach to a wide range of applications. Therefore the PANS modeling approach is used for the current simulation purpose and a desired physical resolution is attempted to be achieved.

In the case of forced convection from a heated body in a cross stream, the geometry of a square prism is the most challenging as it presents all the above-mentioned complex flow phenomena.

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An isothermal flow past a square prism has been widely studied, both experimentally and computationally [7–10]. One of the most significant experimental studies was performed by Lyn et al. [8]. They measured the turbulent flow properties near the wake region of a square cylinder at Re = 22,000 using Laser Doppler Velocimetry (LDV). For numerical studies, mostly LES [9–11] or Hybrid RANS/LES approach, such as Detached Eddy Simulation (DES) [12] and Scale Adaptive Simulation (SAS) [13], are used since the flow is highly unsteady and chaotic. Heat transfer from square cylinder has been mostly investigated experimentally [14–16] and a couple of numerical studies based on LES [17] and SAS modeling [18] are also reported. However, using any of these numerical methods requires sophisticated modeling approach, as these strategies are highly grid dependent.

In industrial applications generating a structured grid for each flow domain is difficult. A structured mesh requires significant time and effort, which forces the industry to use unstructured grid consisting of tetrahedral pyramids with different base shapes. Therefore, as already mentioned, since most hybrid models have strong grid dependence, it becomes very important to choose the type of grid which is to be used. As, the PANS approach is based on the RANS paradigm, it is most likely to be independent of the grid type used, but till date no previous study has been reported to compare the results of unstructured and structured grids. To assess the dependency of the PANS approach on the grid type, both grid strategies are compared in the present paper.

Further the present flow configuration requires special attention towards wall modeling, because an accurate prediction of flow variables in the vicinity of wall is important so as to accurately predict the scalar transportation of heat. This can be achieved in two ways, the first approach is to resolve the flow variables up to the viscous sub-layer by an adequate grid resolution without any wall treatment and the second approach involves the use of wall functions. In the first approach, the computational cost is high due to large number of grids used. The second approach requires smaller computational cost, but the applicability of the wall functions in the separated regions is highly uncertain. In the present paper a comparison of both approaches of near wall modeling is also performed.

In the present paper turbulent heat transfer past a square prism in a cross air stream is studied using the PANS approach. Structured grids with wall functions and unstructured grids with wall resolution are used. The simulations are carried out for Re = 22,000 and ΔT = 30 °C, where ΔT is the temperature difference between the cylinder and free stream. The flow variables predicted are compared with the experimental [8] and LES results [17] and the thermal characteristics are compared with the experimental work [14] and LES results [17]. It has been shown that the PANS approach is a good alternative to LES for industrial problems.

In Section 2, the PANS approach and its derivation from the RANS model is discussed. Different wall modeling approaches used are also introduced in this section. The physical domain and the flow configurations are presented in Section 3. It also discusses the meshing strategy along with the averaging procedure to be used. Section 4 presents the predicted results and their comparisons with the experimental and LES results reported in the literature. Finally the heat transfer phenomenon from a heated wall in a cross flow is explained by a 3D unsteady analysis using the variable resolution PANS methodology.

2. Numerical strategy

2.1. Governing equations

The flow field considered in the present study is treated incompressible, as the Mach number and the temperature difference between the hot surface and free stream flow are small. The governing equations for the conservation of mass, momentum and energy can be written as

$$\frac{\partial V_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial V_i}{\partial t} + V_j\frac{\partial V_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 V_i}{\partial x_j \partial x_j} \tag{2}$$

$$\frac{\partial T}{\partial t} + V_i\frac{\partial T}{\partial x_i} = \alpha\frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right) \tag{3}$$

The heat flux q, is given by:

$$q_i = -\frac{\upsilon\rho C_p}{\mathrm{Pr}}\frac{\partial T}{\partial x_i} \tag{4}$$

where, V_i and T denote the instantaneous velocity and temperature, respectively, p the pressure, ν the viscosity, x_i the three directions, C_p the thermal capacity and α the thermal diffusivity. By applying any arbitrary filter, $(\langle\ \rangle)$, to Eqs. (1)–(3), two extra terms are generated, one the SFS stress and the second the sub-filter heat flux and these are given as $\tau(V_1V_2) = \langle V_1V_2\rangle - \langle V_1\rangle\langle V_2\rangle;\ \tau(V_iT) = \langle V_iT\rangle - \langle V_i\rangle\langle T\rangle$, respectively.

2.2. Partially Averaged Navier Stokes model

As already discussed, the PANS formulation is derived from the two-equation RANS model. A detailed formulation of PANS based on the standard k–ε model can be found in [1,2]. The current PANS model is based on the Menter SST turbulence model [19], which is a blend of the k–ε model far from the wall and Wilcox k–ω model [20] near the wall. A detailed derivation of the PANS approach based on the Wilcox k–ω model [20] is presented in [21] and based on this the PANS SST k–ω evolution equations for the unresolved turbulence kinetic energy (k_u) and the unresolved specific dissipation rate (ω_u) can be given as

$$\frac{\partial(\rho k_u)}{\partial t} + \frac{\partial(\rho U_j k_u)}{\partial x_j} = \widetilde{P_{ku}} - \beta^*\rho\omega_u k_u + \frac{\partial}{\partial x_j}\left(\Gamma_{ku}\frac{\partial k_u}{\partial x_j}\right) \tag{5}$$

$$\frac{\partial(\rho\omega_u)}{\partial t} + \frac{\partial(\rho U_j\omega_u)}{\partial x_j} = \frac{\gamma}{\nu_u}\widetilde{P_{ku}} - \left(\frac{1}{f_\omega} - 1\right)\frac{\gamma\beta^*}{\nu_u}\omega_u k_u - \frac{\beta\rho\omega_u^2}{f_\omega} + \frac{\partial}{\partial x_j}\left(\Gamma_{\omega u}\frac{\partial\omega_u}{\partial x_j}\right) + (1 - F_{1u})2\rho\sigma_{\omega 2}\frac{f_\omega}{f_k}\frac{1}{\omega_u}\frac{\partial k_u}{\partial x_j}\frac{\partial k_u}{\partial x_j} \tag{6}$$

The model coefficients are defined as,

$$\Gamma_{ku} = \mu + \frac{\mu_u}{\sigma_k}\frac{f_\omega}{f_k},\quad \Gamma_{\omega u} = \mu + \frac{\mu_u}{\sigma_\omega}\frac{f_\omega}{f_k},\quad P_{ku} = \tau_{xy}\frac{\partial U_i}{\partial x_j},$$
$$\widetilde{P_{ku}} = \min(P_{ku}; c_l\varepsilon_u) \tag{7}$$

The filter or resolution control parameter used, as defined in [1,2] are the ratios of the unresolved to the total, turbulence kinetic energy and specific dissipation rate and are given by

$$f_k = \frac{k_u}{k};\quad f_\varepsilon = \frac{\varepsilon_u}{\varepsilon};\quad \omega_u = \frac{\varepsilon_u}{\beta^* k_u},\quad f_\omega = \frac{\omega_u}{\omega} = \frac{\varepsilon_u/\beta^* k_u}{\varepsilon/\beta^* k} = \frac{f_\varepsilon}{f_k} \tag{8}$$

The other model constants appearing in the above set of equations (β^*, σ_k, σ_ω, β, σ_ω) are the same as those in the parent Menter SST k–ω model [19]. Further the two blending functions to be used for the PANS model are defined as

$$F_{1u} = \tanh\left(\mathrm{arg}_1^4\right),$$
$$\mathrm{arg}_1 = n\left(\max\left(\frac{\sqrt{k_u}}{\beta^*\omega_u y};\frac{500\nu}{y^2\omega_u}\right);\frac{4\rho\sigma_{\omega 2}k_u}{CD_{k\omega u}y^2}\right) \tag{9}$$